Method and apparatus for determining the cardiac output of a
patient

    The invention relates to a method for determining the
cardiac output of a patient, wherein the patient's respiration
cycle is determined and an indicator is injected into the
patient's bloodstream over a period of at least substantially

5   one respiration cycle, wherein the change in the indicator
value in the bloodstream downstream of the injection point is
measured over a period of a number (n) of respiration cycles
and the injected amount of indicator is established, wherein
the cardiac output is determined on the basis of the measured

10   change in the indicator value, the amount of indicator injected
into the blood and the initial value thereof, as well as to an
apparatus for determining the cardiac output of the patient.

    The measurement carried out in accordance with this method
is known as thermal dilution measurement, wherein a catheter is

15   introduced into the patient's bloodstream, via which catheter a
relatively cold fluid, for example, is injected into the blood
as the indicator. A sensor is attached to the catheter in
question or to a similar catheter downstream of the injection
point, seen in the direction of flow of the blood, by means of

20   which the blood temperature can be measured. In this manner a
so-called thermal dilution curve can be determined, which
indicates the change in the temperature. Since the injected
amount of indicator is known, it is possible to determine the
cardiac output on the basis of the thermal dilution curve. One

25   requirement of the prior art method is that the cardiac output
be constant. In practice it has become apparent, however, that
two major disruptions of the supposedly constant cardiac output
exist; one factor is the pulsating output caused by the action
of the heart, and the other factor is formed by all other low-

30   frequency variations in the cardiac output, which are for
example caused by artificial respiration of the patient.
Generally, the variations in the cardiac output caused by the
action of the heart are not considered to have a disruptive
effect as regards the application of the thermal dilution

method. When artificial respiration is being applied to a
patient by means of an artificial respirator, however, the
cardiac output is influenced to such an extent that it can no
longer be considered to be constant but to be of a fluctuating
5   nature. It is precisely when artificial respiration is being
applied to a patient by means of an artificial respirator that
it is highly desirable that the average cardiac output be
determined with great accuracy, since this value constitutes
one of the criteria in monitoring a patient's condition.
10   Research conducted by J.R.C. Jansen et al, among others,
Intensive Care Med 1990, 16, pp. 422 - 425, has shown that when
the cardiac output is determined by means of the thermal
dilution method, the measuring results may exhibit a dispersion
of 65 - 125% of the average.
15   NL-B-1 005 572 discloses a method and apparatus of the
above kind by means of which the accuracy of the thermal
dilution method can be enhanced by injecting the indicator
exactly over the period of one respiration cycle. By using only
one injection over the period of one respiration cycle, the
20   same result is obtained as by computing the average on the
basis of a number of thermal dilution measurements according to
the conventional method, as for example described in the
aforesaid article.
       The object of the invention is to further improve the
25   method and apparatus of the kind referred to in the
introduction.
       In order to accomplish that objective, the method
according to the invention is characterized in that a first
variation of the indicator value is measured over at least
30   substantially the period of one respiration cycle, preferably
directly prior to the injection, and in that the change in the
indicator value caused by the injection is determined on the
basis of the difference between the change in the indicator
value measured over a period of n times that of the first
35   variation and n times the measured first variation.
       In this manner the accuracy of the thermal dilution method
is further enhanced in that the variation in the indicator
value over a period of one respiration cycle is removed from

the measurement of the indicator value over a period of n respiration cycles. As a result, all cyclical variation in the indicator value is removed from the measuring result, so that only the change in the indicator value that is caused by the
5   injection is obtained.

Preferably, a second variation in the indicator value is measured over a period of at least substantially one respiration cycle, preferably directly contiguous to the measurement of the change in the indicator value, wherein the
10   average of the first and the second variation is determined, which average is used for determining the change in the indicator value rather than the first variation. The advantage thus obtained is that the accuracy is further enhanced and that furthermore the slow drift in the indicator value is removed
15   from the measuring result.

According to another embodiment, a so-called pulse contour measurement is carried out as well, whereby an arterial blood pressure signal is measured. The arterial blood pressure signal is approximately proportional to the cardiac output itself,
20   assuming that the characteristic impedance of the vascular system is constant. This requirement is not met in practice, because said characteristic impedance varies with a relatively large time constant. According to the invention an accurate measurement is made possible in that the arterial blood
25   pressure signal is measured, wherein the values of the stroke volume and of the cardiac output over a period of one heartbeat are computed over a period corresponding to the number (n) of respiration cycles, wherein the average of the computed values is determined, and wherein a proportionality constant is
30   computed from a comparison of the average output value thus computed and the cardiac output value determined on the basis of the change in the indicator value, after which the stroke volume and the cardiac output are multiplied by the computed proportionality constant. Thus the result of the thermal
35   dilution measurement is used as calibration for the pulse contour measurement, as it were, after which the cardiac output can be continuously monitored without subsequent injections by means of the pulse contour measurement. The determination of

the cardiac output from the change in the indicator value can
be repeated periodically, if desired, by carrying out a new
injection and computing the proportionality constant.

5   The invention also provides an apparatus for determining
the cardiac output of a patient, which apparatus comprises a
processing unit having a control output for controlling
injection means, a first sensor for measuring the change in an
indicator value in the patient's bloodstream and a second
sensor for determining the patient's respiration cycle, wherein
10   the processing unit is arranged for measuring the change in the
indicator value in the bloodstream downstream of the injection
point over a number (n) of respiration cycles, establishing the
injected amount of indicator and determining the cardiac output
on the basis of the measured change in the indicator value, the
15   amount of indicator injected into the blood and the initial
value thereof, which apparatus is according to the invention
characterized in that the processing unit is arranged for
measuring a first variation of the indicator value over at
least substantially one respiration cycle, preferably directly
20   prior to the injection of the indicator, and determining the
change in the indicator value resulting from the injection on
the basis of the difference between the measured change in the
indicator value measured over a period of n times that of the
first variation and n times the measured first variation.

25   The invention will be explained in more detail hereafter
with reference to the drawing, which schematically shows an
exemplary embodiment of the apparatus according to the
invention.

Figure 1 is a block diagram of an embodiment of the
30   apparatus according to the invention.

Figures 2 and 3 are diagrams which illustrate the method
according to the invention.

It is noted that the term respiration cycle as used within
the framework of the description and the claims is understood
35   to mean a natural respiration cycle as well as an artificial
respiration cycle. The indicator may be a cold fluid, but also
any other suitable indicator, such as a saline solution or a
glucose solution or a colouring agent may be used. Although a

cold fluid is used as the indicator in the present embodiment,
it is also possible to use another indicator, therefore.

Figure 1 shows apparatus for measuring the cardiac output
of a patient, which apparatus comprises a processing unit 1,
5   for example in the form of a PC with suitable software. The
processing unit 1 comprises an input/output 2 for controlling
injection means 3 (schematically indicated), by means of which
a cold fluid can be injected into the patient's bloodstream. To
this end a thermal dilution catheter is introduced into the
10   patient's blood vessel in a usual manner. The temperature of
said cold fluid is measured by means of a sensor 4, which is
connected to processing unit 7. The catheter (not shown) is
fitted with a sensor 7 located at some distance from the
injection opening, by means of which the temperature of the
15   blood downstream of the injection opening can be measured.
Sensor 7 is connected to an input 8 of an amplifier 9, whose
output signal is likewise supplied to the processing unit 1.
Using the apparatus described so far, a so-called thermal
dilution curve can be determined, from which the cardiac output
20   can be computed on the basis of the injected amount of cold
fluid and the temperature of said fluid. A plurality of
injections of cold fluid would be required in order to be able
to determine the average cardiac output. As is disclosed in NL-
B-1 005 572, however, it is possible to determine the thermal
25   dilution curve by means of only one injection over the period
of one respiration cycle.

To this end the apparatus disclosed herein comprises a
sensor 10, which is connected to processing unit 1 via an
amplifier 11. Sensor 10 measures a respiration cycle-dependent
30   signal. Such a sensor can for example measure the concentration
of carbon dioxide, the strength of the air flow, the
temperature of the respiration air or the like. The processing
unit 1 now controls the injection means 3 in such a manner that
one injection of indicator is carried out accurately for the
35   duration of one respiration cycle and subsequently records the
change in the concentration of the indicator for a number n of
respiration cycles.

Figure 2 shows a temperature/time diagram wherein the

temperature change is marked off as a function of the time. The
average cardiac output is measured by one controlled injection
for the duration of a respiration cycle and it is not necessary
to carry out a number of measurements. In the example of Figure
5   2 the period during which the change in the concentration is
recorded is indicated T1. This period runs from 6=4 to 6=12.

When a cold fluid is injected as the indicator, the
following equation applies:

$$Q_i \, \rho_i \, S_i \, (T_b \; T_i) = Q'_b \, \rho_b \, S_b \int \Delta T_b(t) dt$$

10   wherein Q_i is the injected volume, ρ is the specific heat and S
is the specific mass of (i) injected matter and (b) blood,
respectively, T is the temperature, Q'_b is the cardiac output
and ΔT_b is the change in the temperature of the blood brought
about by the injection of cold fluid.

15   Rearrangement of the formula shows how the cardiac output
can be computed.

$$Q'_b = Q_i \frac{\rho_i \, S_i \, (T_b T_i)}{\rho_b \, S_b \int \Delta T_b(t) dt}$$

This formula forms the basis for most thermal dilution "cardiac
output" computers.

20   Research has shown that it is not possible to achieve
accurate measuring results in this manner, since the pulsating
cardiac output fluctuates due to the natural respiration or
artificial respiration via a ventilator. This is schematically
shown in Figure 2. In this case the temperature change also
25   includes a temperature variation which is not caused by the
injection. This influence on the respiration can be removed by
measuring the area below the measured temperature curve over a
period of exactly one respiration cycle, preferably directly
prior to the injection of the cold fluid. In the embodiment as
30   shown in Figure 2 injection takes place at t=4, and
consequently area A is measured first for the duration of
period T2. The determination of area B under the temperature

curve is started at the time of injection t=4, and lasts over a period of a number n of respiration cycles until t=12. The area resulting from the injection of the cold fluid will then be Area-Dil = B - n x A.

5   The cardiac output is then computed as:

$$Q'_b = Q_t \frac{\rho_i S_i \ (T_b T_i)}{\rho_b S_b \ Area - Dil}$$

The influence of slow temperature drift resulting from an increase or decrease of the body temperature, for example, can

10   furthermore be eliminated by measuring the temperature change over a period of exactly one respiration cycle directly prior to as well as directly contiguous to the injection. This situation is shown in Figure 3. Both area A and area C are thereby measured over period T2 and over period T3,

15   respectively, so that the area resulting from the injection of the cold fluid will then be Area-Dil = B - n/2 x (A + C).

It is therefore possible with the method and apparatus disclosed herein to measure the average cardiac output of a patient with great accuracy by means of only one injection of

20   indicator.

According to a very advantageous embodiment the apparatus is also fitted with a sensor 12, which is connected to the processing unit 1 via an amplifier 13. Sensor 12 measures the arterial blood pressure signal, for example in the aorta. It is

25   known per se that it is possible to compute the noncalibrated value of the stroke volume and the cardiac output from said arterial blood pressure signal over a period of one pulsation of the heart. This is for example disclosed in US-A-3 841 313. In the apparatus disclosed therein, the computed values of the

30   cardiac output are recorded over the period of the measurement of the thermal dilution curve, and the average thereof is determined. Then a proportionality constant is computed by the processing unit 1 by comparing the cardiac output value thus computed with the cardiac output which has been determined by

35   means of the thermal dilution method. Then the computed values

for the stroke volume and the cardiac output resulting from the measurement of the arterial blood pressure can be continuously converted into accurate measurements by means of said proportionality constant.

5   If desired, the processing unit can be programmed in such a manner that a thermal dilution determination is carried out periodically in the above-described manner, and a new proportionality constant can be determined.

It is noted that the measuring results can be displayed on
10   a screen 14, if desired. Furthermore it is noted that the thermal dilution measurement can be started automatically or by giving a suitable command, for example via a keyboard 15.

The invention is not restricted to the above-described embodiment as shown in the drawing, which can be varied in
15   several ways without departing from the scope of the invention.